BBC RD 1977/33

RESEARCH DEPARTMENT REPORT

New block-codes for digital tape recording

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THE BRITISH BROADCASTING CORPORATION September1977

BBC RD 1977/33
UDC 621.395.625.3:
621.397.61:
621.391

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M.E. Bailey, B.A.

Summary

This report describes the theoretical and practical performance of certain digital codes potentially suitable for digital sound and television recording on magnetic tape. The adopted criterion of performance is the attainable packing-density of user-data, i.e. source data, consistent with an adequate bit-error rate. Two particular block-codes were found which provided a 20% increase in the user-data packing-density relative to that obtained with the widely used delay modulation (Miller Code).

Issued under the authority of

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BRITISH BROADCASTING CORPORATION

September 1977

(PH-180)

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1. Introduction

Digital recording on magnetic tape is beginning to challenge the use of analogue tape-machines for recording broadcast-quality sound and television signals. A recording method with a high packing density of digital data, compared with that used in the computer industry, is required to make this viable. When binary signals are to be recorded on magnetic tape, the characteristics of the recording channel make it necessary to use special modulation or coding prior to recording.[1] The purpose of the coding is to enable reliable retrieval of the original binary signal and clock waveform; the coding is normally done digitally. Selecting a modulation code to maximise the linear packing density of the binary signal data on the tape is one of the main problems in designing a high-density recording system.

The subject of this Report is to contribute to the search for an optimum binary coding for tape-recording. Work has been confined to block-codes – those in which the binary signal-data stream is divided into blocks of k bits, each of which is transformed into n bits where $n > k$, thereby generating the block-coded stream. Such a block code is labelled (n, k) where n is known as the dimension. The transformation is made using a 'look-up table' or 'code-book', and it is thus quite general.

The constraints placed upon the selection of a code-book by the characteristics of the recording channel are discussed with two representative code-books chosen to demonstrate the benefit in terms of packing density. Their effectiveness was measured experimentally as a function of error rate introduced by the system and the results were compared with those for delay modulation,[2] also known as the Miller code, using the same recording system. Finally the factors of system noise and error extension are examined for the two code-books and delay modulation.

2. The digital recording channel

When selecting a modulation code it is important to bear in mind the limitations of the recording channel, outlined below; in practice, these limitations are somewhat flexible because minor adjustments of the recording-channel parameters can be made to suit a given modulation code. The complete digital recording channel consists of the apparatus required to receive, record, replay and reconstitute binary data. It comprises a digital to analogue interface for recording, the recorder itself, equalisation and data retrieval to interpret the replayed analogue signals correctly as digits.

2.1. Limitations of a tape-recorder

The recorder itself comprises record-heads, magnetic tape, tape transport, replay heads and associated amplification. The main limitations of a recorder are the bandwidth, various sources of noise, and the presence of isolated defects, such as dropouts; tape-speed errors in a digital recorder can now be readily corrected.[3] Digital recording is conventionally done by magnetising the tape to saturation; a fairly detailed examination of the techniques and main limitations of saturation recording is given in Reference 4, and so here we shall restrict the discussion to a brief summary of the points relevant to the choice of recording codes.

The high-frequency response is limited mainly by the finite size of the replay head gap, and to a lesser extent, by the thickness of the magnetic coating of the tape which is typically several gap widths thick. Binary coded signals, as shown in Fig. 1(a), are recorded as saturation flux-reversals in the tape, and the flux-reversals become increasingly indistinct as the penetration of the recorded field into the tape-coating increases. The high-frequency

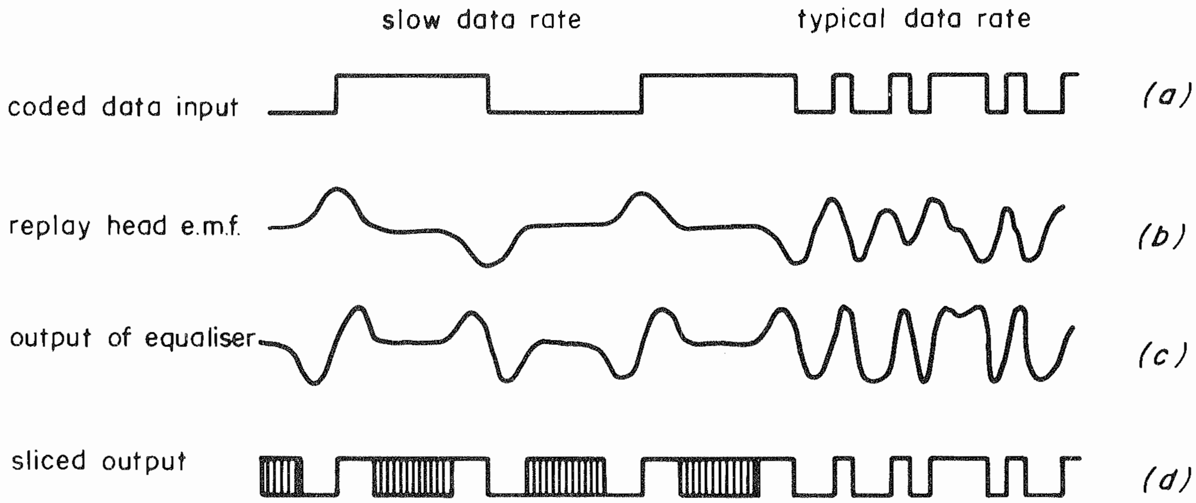


Fig. 1 - Data recovery from tape

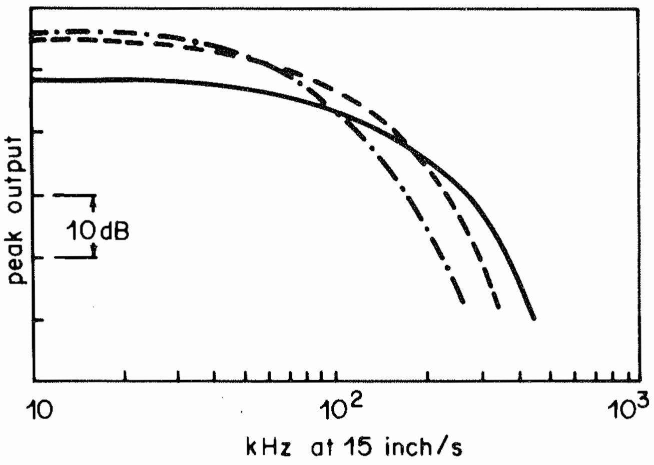


Fig. 2 - Response/frequency characteristic for a square wave recording as a function of recording current

———	15 mA	peak to peak
— — —	28 mA	recording
—·—	40 mA	current

response for a particular replay head can therefore be improved by concentrating the saturated region of the coating as close to the surface as possible. Such partial-penetration recording is done by critical adjustment of the current in the record head, which affects the frequency-response characteristic for a square-wave input as shown in Fig. 2.

The low-frequency response of the channel is governed by the law of electromagnetic induction. The replay e.m.f. is proportional to the rate of change of flux, and thus it is the flux-reversals of the recorded signal which induce a replay e.m.f. This, together with the high-frequency response, results in a replay signal as shown in Fig. 1(*b*).

The maximum data rate for a given modulation code and recording channel is limited by the onset of data errors. There are several causes for these errors. Firstly, there is random noise which is generated mainly by the tape replay head and its amplifier. Secondly, there is a correlated noise effect known as 'peak-shifting' which becomes significant at high data rates. Peak-shifting is the tendency for a gap between two closely spaced flux transitions to open up due to magnetic interaction. The effect on replay is a loss of timing information, or timing jitter. This can be sufficient to cause clocking errors. Thirdly, dropouts can occur during recording and/or replaying, which give a loss of signal. The major cause of dropouts is defects in the tape coating; these are typically 0·5 mm in diameter, and they can therefore give rise to an error-burst which is hundreds of binary digits long. Dropouts account for an average error rate of about 1 in 10^5.

2.2. Equalisation

The frequency response described above can be improved by replay equalisation, but the useful bandwidth obtainable is limited by channel noise and the need for sufficient timing information for a particular modulation code. Complexity is another constraint affecting equalisation as many parallel tracks may be required to record one programme and each track requires its own equaliser. For this reason relatively simple instrumentation was used for equalisation in this work; see Appendix, Section 8.2 for details.

The effect of good equalisation is to maximise the 'eye height' for the retrieved coded signal. This can be achieved most simply by differentiating the replay signal. The differentiated replay signal, shown in Fig. 1(*c*) passes through zero at instants corresponding to the original data transitions, shown in Fig. 1(*a*), because it is effectively a double derivative of the original NRZ signal. The high frequency cut-off ensures that the equalised signal never falls back to zero between transitions, provided the length between flux-transitions or 'string length' is limited. The string length is adequately short on the right hand side of Fig. 1 and too long on the left.

2.3. Retrieval of the binary signal

Since the equalised signal is made to pass through zero volts at data transitions, binary data can be retrieved with transitions correctly spaced by slicing the waveform at this level to retrieve the binary data. There are two problems, however.

Firstly, as longer string lengths are permitted in the recorded coded original, the signal presented to the slicer using the equalisation described will tend towards that shown in the left side of Fig. 1(*c*), resulting in severe loss in noise margin and spurious binary pulses as shown in the left side of Fig. 1(*d*). It was found that this limitation on string length placed the major constraint on code selection. It is not known whether an equalisation using other principles could relax this contraint.

Secondly, a much longer time-scale effect can occur if the coded signal contains appreciable energy at low frequencies. The low-frequency loss in the response of the recording channel may be considered as a.c. coupling in the system. Any low-frequency content of the coded signal will therefore tend to modulate the replay signal. This has the same effect as modulating the slicing level, and it is sometimes described as 'galloping base-line'. The result is again a poorer noise margin.

2.4. Regeneration of the clock waveform

To interpret the sliced binary waveform it is essential to regenerate a clocking waveform. In principle a modulation code could be devised with a spectral null at which a pilot tone could be situated.[1] For a generalised block-code there are no such nulls, and the clocking waveform must be deduced from the retrieved data itself. In practice, this means that the coded signal must have many data transitions.

3. The choice of code-books

3.1. Desirable properties of a recording code

Further to the discussion on recording channel limitations in Section 2, the following are desirable basic

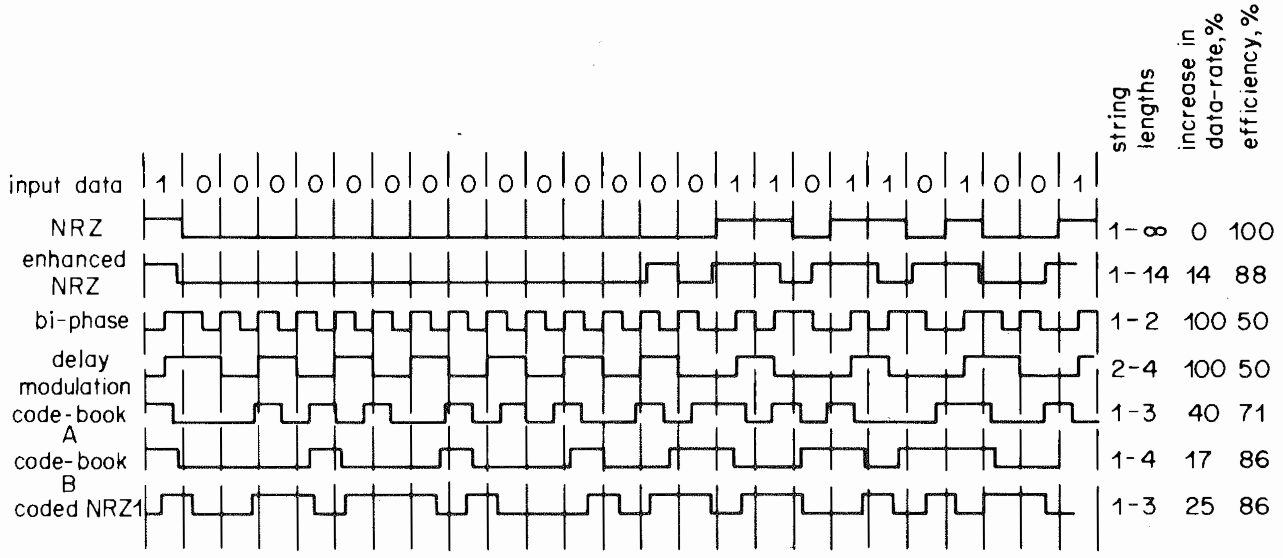


Fig. 3 - Illustrations of modulation codes

properties for a modulation code for use in magnetic tape-recording:—

(a) Short maximum string length.

(b) Well dispersed ones and zeroes in the coded data stream, i.e. low l.f. content.

(c) High efficiency where efficiency is defined as the ratio of the user-data rate, i.e. the data rate presented by the user of the channel, to the coded-data rate, i.e. the data rate applied to the magnetic recording head.

(c) Suitability for economic instrumentation.

Various well-established modulation codes such as enhanced NRZ,[5] biphase, and delay modulation (the Miller code) have these desirable properties, but not to an optimum degree in all respects; delay modulation has probably been the most widely used for high-density tape-recording applications. These three codes, and the codes to be described below (code-books A and B and 'coded NRZ 1') are illustrated in Fig. 3 showing the string lengths expressed in units of bit-intervals of coded-data, the increase in data rate due to coding, and the efficiency k/n. The (n, k) values in this figure for enhanced NRZ, code-book A, code-book B and 'coded NRZ 1' are (8, 7), (7, 5), (7, 6) and (5, 4) respectively.

3.2. Selecting a block-code code-book

For an (n, k) block-code, 2^k acceptable codes must be selected from the total number 2^n, to accord as far as practicable with the desired properties discussed in Section 3.1. For most methods used for data recovery the string length is the most important parameter. The numbers of codes valid for various ranges of string length were computed and are listed in Table 1, under NRZ. ('Coded NRZ 1' included in this Table is discussed in Section 3.4.) It should be noted that a string length of l can arise from either l successive zeroes (or ones) within a code word, or $l-m$ successive zeroes (or ones) at the end of a code word followed by m successive zeroes (or ones) at the beginning of the next code word. This effect results in codes with longer blocks (words) being more efficient; in other words, the shorter the block length, the lower are 2^k and k/n.

TABLE 1

Code Selection by String Length

Dimension	Total Number of Codes	Number of Codes 2^k					
		NRZ String Lengths			Coded NRZ 1 String Lengths		
n	2^n	1–2	1–3	1–4	1–2	1–3	1–4
4	16	4	6	10	5	9	11
5	32	6	12	18	8	17	21
6	64	10	22	36	13	31	41
7	128	16	40	70	21	57	79
8	256	26	74	134	34	105	152
9	512		136			193	
10	1024		250			355	

TABLE 2

Block-code Code-books

BI-PHASE (2, 1)

data	code
0	1 0
1	0 1

CODE BOOK A (7, 6)

data	code
0 0 0 0 0	0 1 0 0 1 0 1
0 0 0 0 1	0 1 0 0 1 1 0
0 0 0 1 0	0 1 0 1 0 0 1
0 0 0 1 1	0 1 0 1 0 1 0
0 0 1 0 0	0 1 0 1 0 1 1
0 0 1 0 1	0 1 0 1 1 0 0
0 0 1 1 0	0 1 0 1 1 0 1
0 0 1 1 1	0 1 0 1 1 1 0
0 1 0 0 0	0 1 1 0 0 0 1
0 1 0 0 1	0 1 1 0 0 1 0
0 1 0 1 0	0 1 1 0 0 1 1
0 1 0 1 1	0 1 1 0 1 0 0
0 1 1 0 0	0 1 1 0 1 0 1
0 1 1 0 1	0 1 1 0 1 1 0
0 1 1 1 0	0 1 1 1 0 0 1
0 1 1 1 1	0 1 1 1 0 1 0
1 X X X X	COMPLEMENTS

CODE BOOK B (7, 5)

data	code
0 0 0 0 0 0	0 0 1 0 0 0 1
0 0 0 0 0 1	0 0 1 0 0 1 0
0 0 0 0 1 0	0 0 1 0 0 1 1
0 0 0 0 1 1	0 0 1 0 1 0 0
0 0 0 1 0 0	0 0 1 0 1 0 1
0 0 0 1 0 1	0 0 1 0 1 1 0
0 0 0 1 1 0	0 0 1 1 0 0 1
0 0 0 1 1 1	0 0 1 1 0 1 0
0 0 1 0 0 0	0 0 1 1 0 1 1
0 0 1 0 0 1	0 0 1 1 1 0 0
0 0 1 0 1 0	0 1 0 0 0 1 0
0 0 1 0 1 1	0 1 0 0 0 1 1
0 0 1 1 0 0	0 1 0 0 1 0 0
0 0 1 1 0 1	0 1 0 0 1 0 1
0 0 1 1 1 0	0 1 0 0 1 1 0
0 0 1 1 1 1	0 1 0 1 0 0 1
0 1 0 0 0 0	0 1 0 1 0 1 0
0 1 0 0 0 1	0 1 0 1 0 1 1
0 1 0 0 1 0	0 1 0 1 1 0 0
0 1 0 0 1 1	0 1 0 1 1 0 1
0 1 0 1 0 0	0 1 0 1 1 1 0
0 1 0 1 0 1	0 1 1 0 0 0 1
0 1 0 1 1 0	0 1 1 0 0 1 0
0 1 0 1 1 1	0 1 1 0 0 1 1
0 1 1 0 0 0	0 1 1 0 1 0 0
0 1 1 0 0 1	0 1 1 0 1 0 1
0 1 1 0 1 0	0 1 1 0 1 1 0
0 1 1 0 1 1	0 1 1 1 0 0 1
0 1 1 1 0 0	0 1 1 1 0 1 0
0 1 1 1 0 1	0 1 1 1 0 1 1
0 1 1 1 1 0	0 1 1 1 1 0 0
0 1 1 1 1 1	0 1 1 1 1 0 1
1 X X X X X	COMPLEMENTS

CODED NRZ 1 (5, 4)

data	code
0 0 0 0	1 1 0 0 1
0 0 0 1	1 1 0 1 1
0 0 1 0	1 0 0 1 0
0 0 1 1	1 0 0 1 1
0 1 0 0	1 1 1 0 1
0 1 0 1	1 0 1 0 1
0 1 1 0	1 0 1 1 0
0 1 1 1	1 0 1 1 1
1 0 0 0	1 1 0 1 0
1 0 0 1	0 1 0 0 1
1 0 1 0	0 1 0 1 0
1 0 1 1	0 1 0 1 1
1 1 0 0	1 1 1 1 0
1 1 0 1	0 1 1 0 1
1 1 1 0	0 1 1 1 0
1 1 1 1	0 1 1 1 1

A second selection step should be taken according to property (b) in Section 3.1, by choosing codes with nearly equal numbers of well-distributed ones and zeroes; a measure of the distribution is the moment of the code about its centre, treating zeroes and ones as weights.

Finally, due account must be taken of the cost-effectiveness of instrumentation to execute the requisite arithmetic and to give adequate data storage.

3.3. The two code-books chosen

Two code-books are discussed in the remainder of this report, and for instrumental reasons, a code-block length of seven was chosen for both code-books. Based on the criteria given above, code-book A, (7, 5), with string lengths of 1 to 3 was selected from those 7-bit codes with three or four zeroes. Code-book B, (7, 6), with string lengths of 1 to 4 was selected from those 7-bit codes with two, three or four zeroes.

Compared with code A, the string length restriction for code B was increased to improve the efficiency k/n. Both of these block codes, and the effective code-books for 'coded NRZ 1' (see below), are listed in Table 2.

Only half of each code-book is listed, the other half being derived by complementing both the data and the code words.

The low-frequency content of code-books A and B can be compared by determining their theoretical power spectra.* These are shown in Fig. 4, which confirms that code-book A contains less l.f. content than code-book B, due mainly to the shorter string lengths involved. Bi-phase coding, which has zero d.c. content, is also shown, and it can be seen that code-books A and B differ adversely from bi-phase at very low frequencies only. All three spectra are compared in this figure for a given coded-data rate.

* a method by R.E. Davies was used.

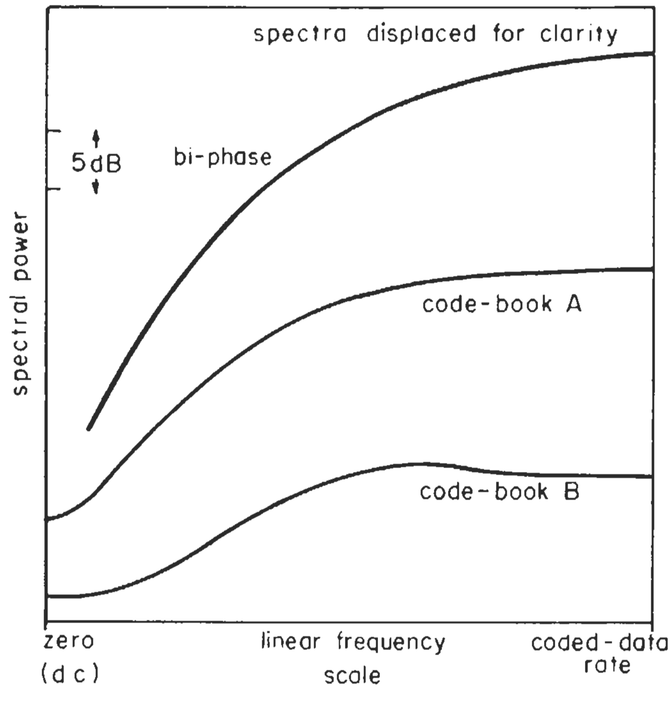


Fig. 4 - Code-book theoretical spectra

3.4. An alternative modulation system using block codes

In an attempt to improve efficiency, an alternative approach using block coding has been suggested,[6] but not yet implemented at high data-rates. Blocks of k data bits are transformed to n code bits as above, but an operation then follows to generate an NRZ 1 code, and it is this that is recorded. To produce this 'coded NRZ 1' transitions are made in the centre of bit cells containing ones in the block code-words. The numbers of valid codes using 'coded NRZ 1' giving NRZ 1 with various ranges of string length were computed and are shown in Table 1. String lengths in the range 1 to m are given by data which has no more than $m-1$ successive zeroes before the NRZ 1 operation.

The examples in Table 1 show a greater proportion of acceptable code words using 'coded NRZ 1' than NRZ for a given dimension n and maximum string length. It is not known whether this is a general result and the apparent superiority in efficiency may be offset by unsuspected practical disadvantages.

The reference quoted suggests the use of a set of 16 five-bit codes, (i.e. a (5, 4) code) resulting in recorded string lengths of 1 to 3. The increase in efficiency over that of code-book A which has the same range of string lengths would suggest a possible increase in packing density performance of 12%. The codes are listed in Table 2, and the resulting recorded sequence for a sample of user-data is shown in Fig. 3.

4. The experimental system

Measurements were made using code-books A and B and delay modulation on a single, isolated-track recording channel, described in the Appendix. The experimental equipment is shown schematically in Fig. 5. The channel performance for a particular modulation code was tested using two pseudo-random sequence (m-sequence) generators, one to generate NRZ user data and the other to test this once they had been coded, recorded and then decoded.

4.1. Decoding the phase

In order to interpret the replayed data stream in a practical recorder, framing information is inserted or 'stuffed' prior to recording. Similar framing, or phase information is required to interpret many modulation codes. In the case of delay modulation, the correct one of two possible decoding phases can be determined by the uniqueness of the coded version of '101' in the original user data.[2] This sequence can be included in a framing word to ensure its occurrence once per framing length in

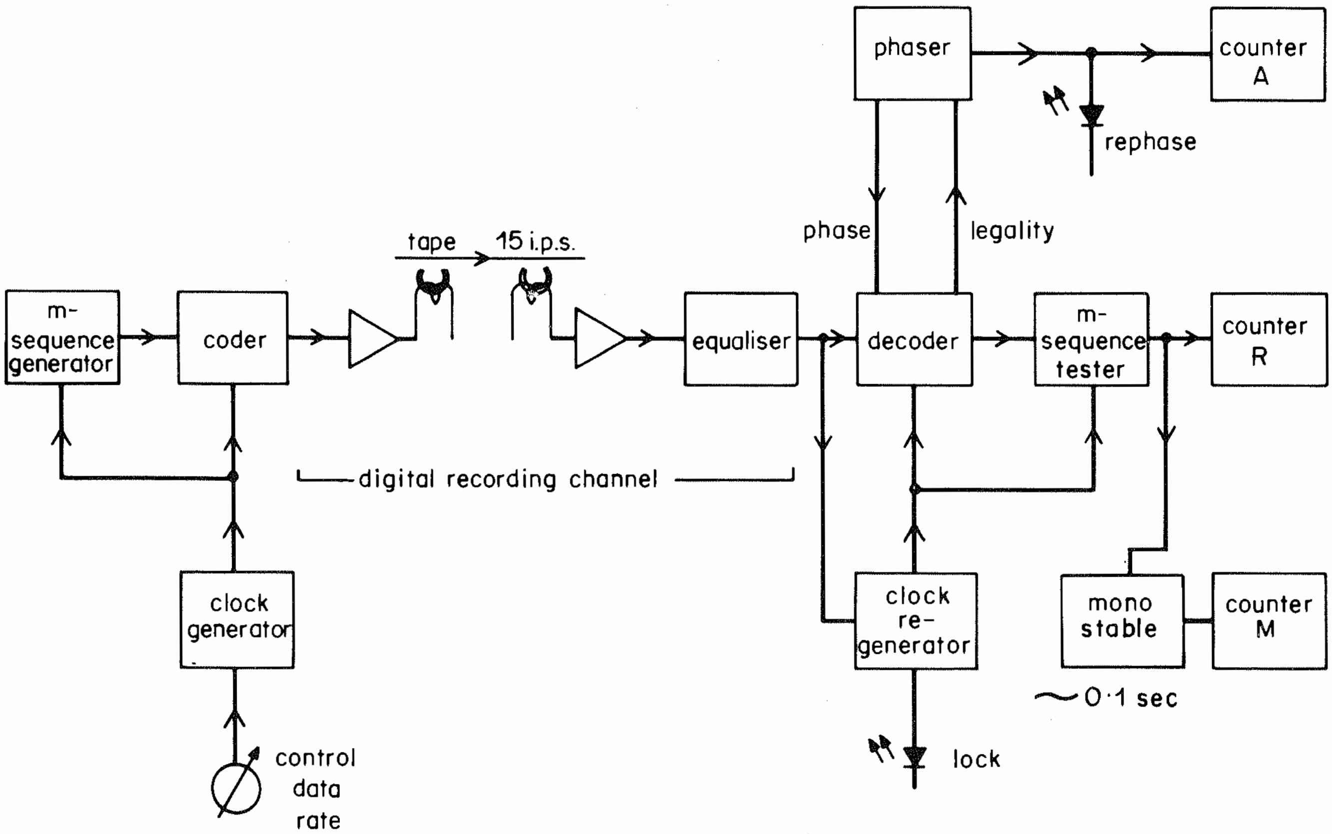
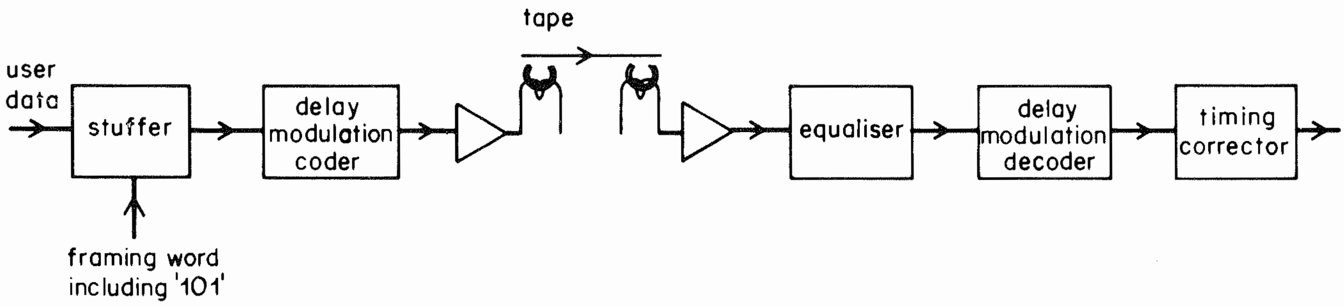
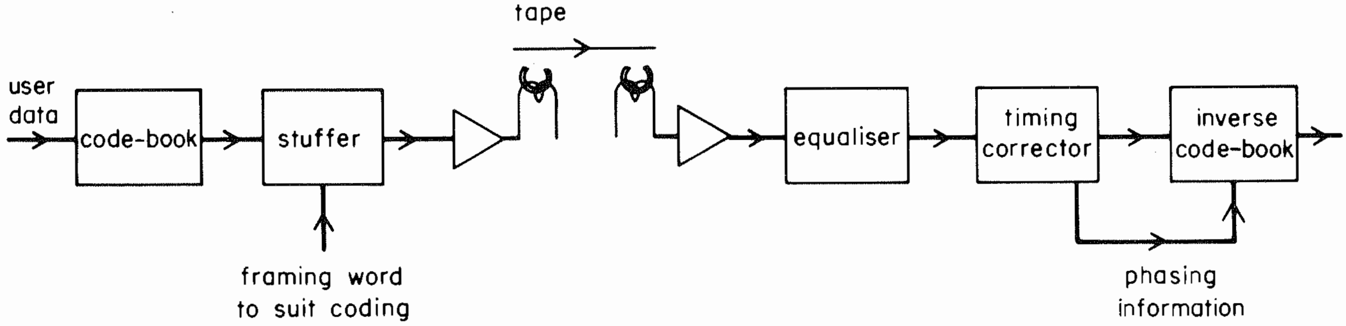


Fig. 5 - The experimental system



(*a*)



(*b*)

Fig. 6 - Practical modulation systems
(*a*) Delay modulation (*b*) Block coding

practical data. A practical delay modulation channel could then take the form of Fig. 6(*a*).

In the case of a block code (n, k), there are in general a choice of n decoding phases. Only one is correct, and that phase can be derived by use of framing information. The best place to insert this framing word is after coding as shown in Fig. 6(*b*), because then it need not be one of the code-book words.

To avoid the instrumentation of framing-word insertion, detection and removal in the experimental block-code apparatus, an alternative method for ensuring the correct decoding phase was used.* This method relied on the presence of 'illegal' code words in incorrect phases to deduce the correct phase. Such phasing information is available relatively infrequently compared with the framing for delay modulation mentioned above. The result of this is that, if an incorrect phase is entered during an error burst, error extension can occur until the correct phase is found. The average extension is the average length between phasing information, which varies from code to code, but was found to be about 66 and 155 bit-intervals of user data for code-books A and B respectively.

4.2. Counting the errors

The block diagram of Fig. 5, shows three counters, each of which were used to obtain an indication of the number of errors during a representative measurement time. The functions of each counter are now described.

The counter R gives a direct measure of the error rate as indicated by the m-sequence tester. Once the internal shift register of the tester is full, subsequent binary digits entering the register are compared with those generated in the tester, which are based on the contents of the register. Thus a single error input gives rise to a number of error indications, as it propagates through the shift register, whilst a burst error input may result in a number of indications very nearly equal to the number of input errors. It has been shown** that for the particular m-sequence tester in use for an input of uncorrelated errors at a rate p,

$$\frac{\text{indicated error rate}}{\text{actual error rate}} = q = 3\left(1 - 2p + \frac{4p^2}{3}\right) \qquad (1)$$

Thus the counter R over-reads by between 1 and 3 depending on the proportion of burst errors.

Bursts of errors, hundreds of bit-intervals in duration, can occur due to tape dropouts in high-density digital recording. To obtain an error count which would reduce such error bursts effectively to a single error, the error indication to counter R, was used to trigger a monostable with a duration of about 10 000 bit-intervals, and the number of monostable pulses was recorded on counter M. This number M thus gave a better indication than R of code performance, virtually removing the effect of dropouts.

* see Appendix, Section 8.5, for description of operation.

** Private communication from J.P. Chambers.

The number of changes in decoding phase was recorded on the counter A. This quantity can be used (see Section 5.2) as an alternative, approximate means of correcting count R to allow for dropouts and the error extension outlined in Section 4.1.

5. Experimental results

5.1. Presentation of results

For each coding system, pseudo-random data was recorded at a number of data rates corresponding to packing densities of user data in the range 20 to 40 k bit/inch (0·8 to 1·6 k bit/mm*). The replay signal was obtained by direct monitoring off the tape, and the counts A, R and M (see Fig. 5) were accumulated for several separate representative periods during the first replay pass of the tape. At low error rates, a period of at least 10 minutes was needed. For comparison, all counts were normalised as if for 10 minutes. The variation in the normalised error counts for a particular set of conditions was always about one order of magnitude, and so a logarithmic scale of error counts has been used for clarity in presenting the results graphically. To collate this data, 'optimistic' and 'pessimistic' lines were drawn to enclose between 80% and 90% of recorded points.

5.2. Corrections to indicated results and discussion of performance

Graphs of the normalised, indicated (uncorrected), error-rate R for code-books A and B and for delay modulation are shown in Fig. 7. The broken line is the locus of an error rate of 1 in 10^5.

The correction given by Equation (1) was not made to individual results, mainly because it was found to be small compared with measurement variations. However the correction was applied in reverse to the 1 in 10^5 locus for each graph using a somewhat arbitrary value of 2·5 for q to allow for burst errors, so that the graphs are self consistent.

As mentioned above, counter M gives a value which virtually eliminates the effect of dropouts, which would otherwise mask differences between coding systems. M, which is approximately the number of single errors, counting error bursts as single errors, is plotted in Fig. 8. To facilitate comparison between Figs. 7, 8 and 9, M has been normalised for Fig. 8 by multiplying its values by the average value of R counts per M count over all the data taken.

An alternative correction giving a fairer comparison is to compensate simultaneously for dropouts and the error extension in code-book decoding outlined in Section 4.1. (Error extension for delay modulation can be ignored.) The compensation is effected by multiplying the number of rephase commands A by the appropriate mean rephase

* It is still conventional to quote data-packing densities in kilobits per inch, in this context.

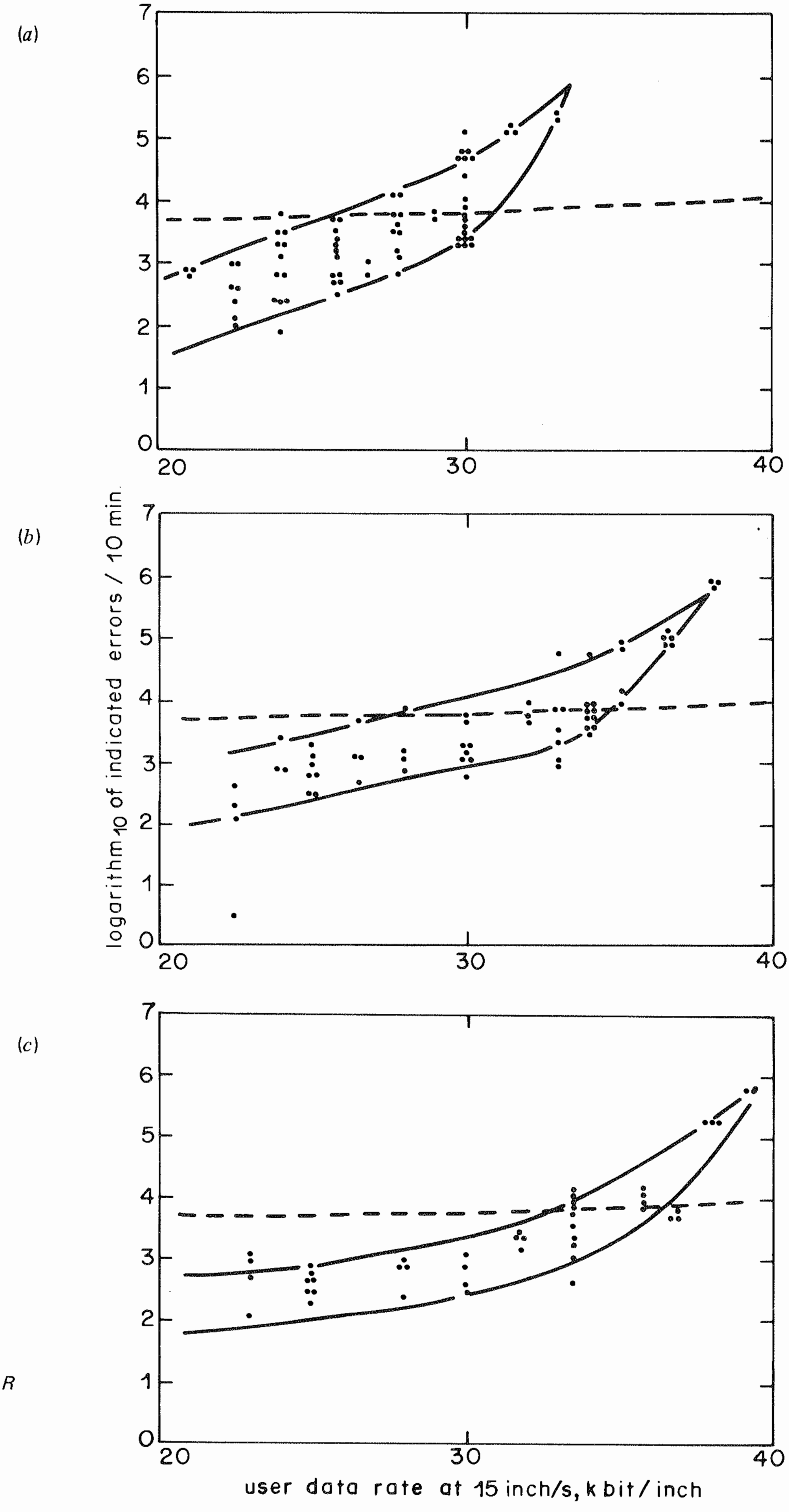


Fig. 7 - Normalised error count R versus packing density

(*a*) Delay modulation

(*b*) Code-book A

(*c*) Code-book B

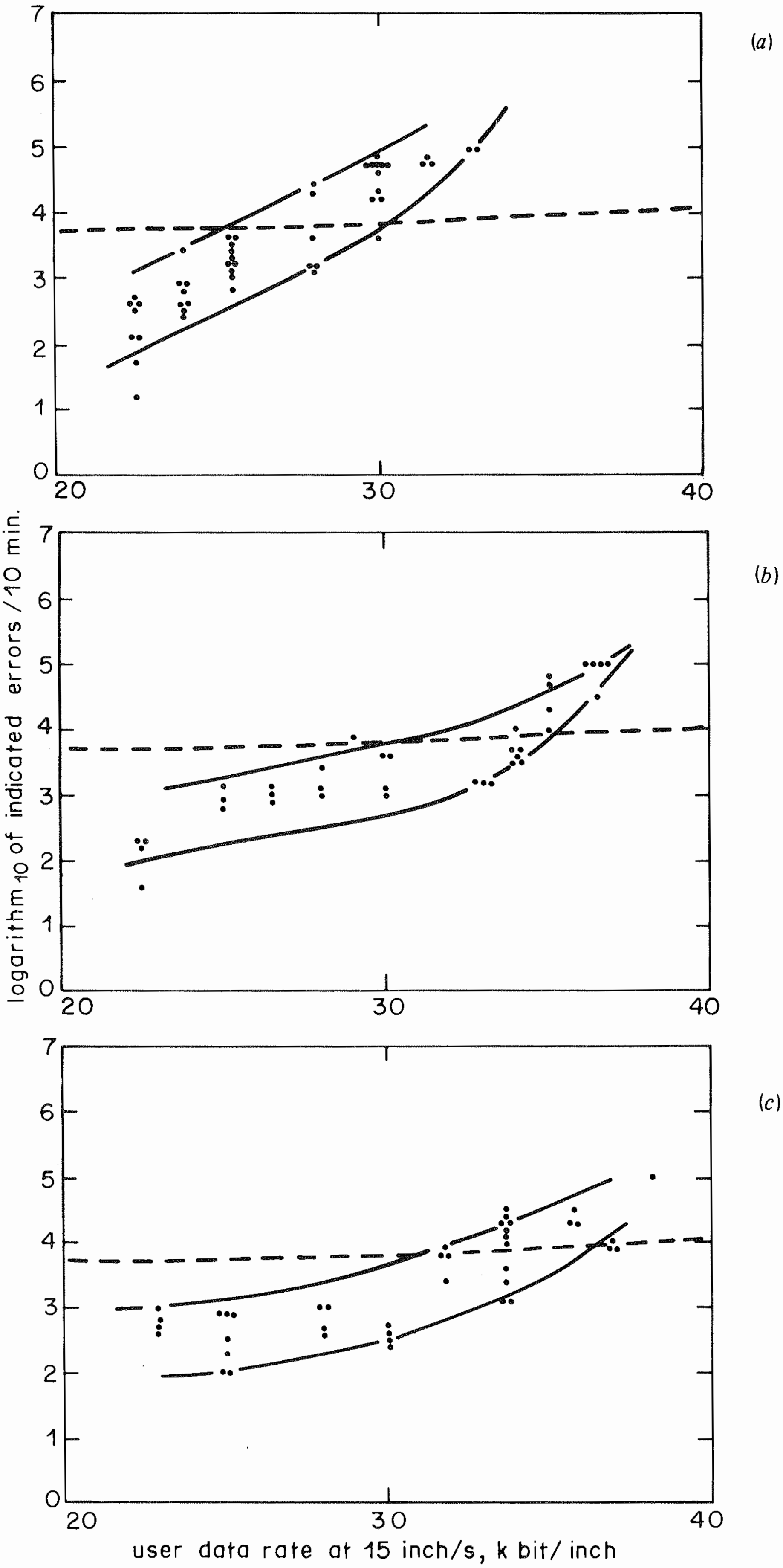
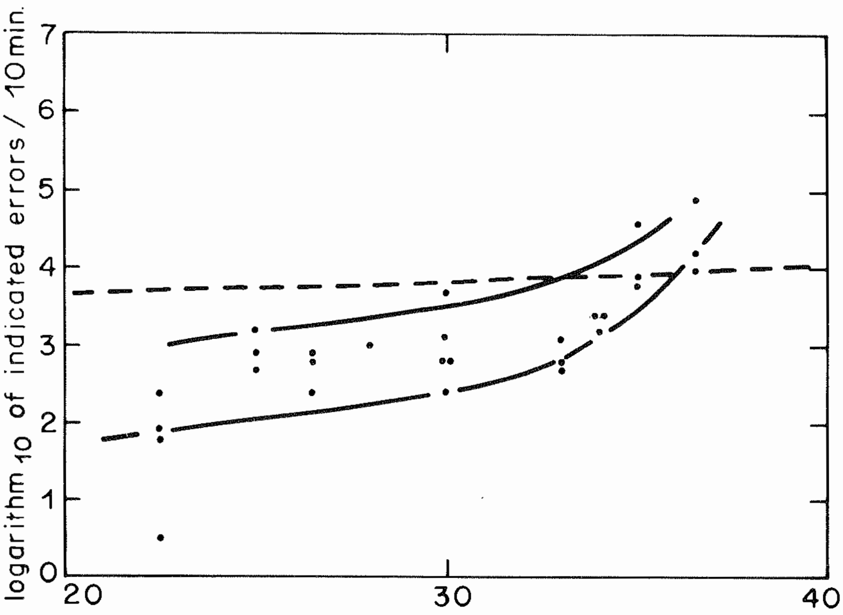
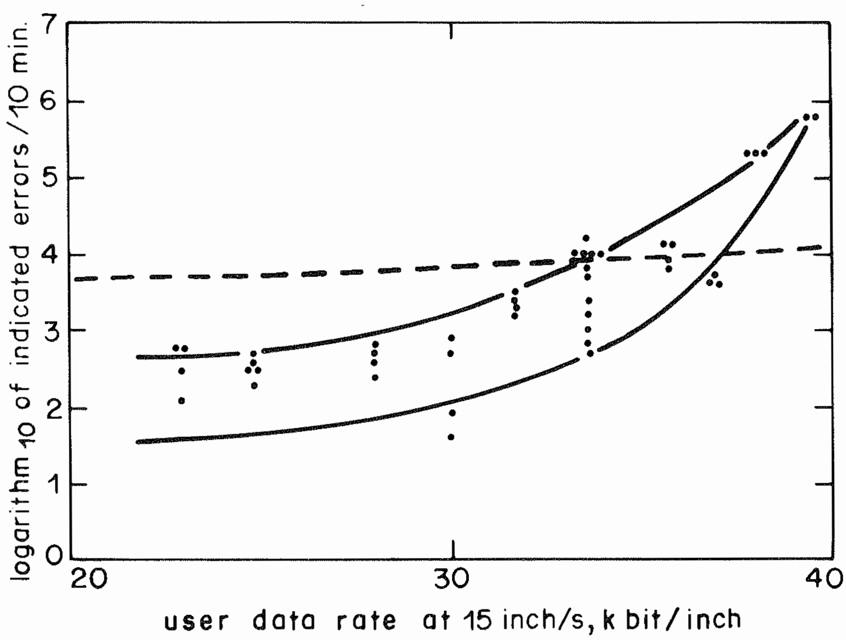


Fig. 8 - Normalised burst error count M versus packing density
(a) Delay modulation
(b) Code-book A
(c) Code-book B



(*a*)



(*b*)

Fig. 9 - Rephase-corrected error count versus packing density
(*a*) Code-book A
(*b*) Code-book B

length (66 and 155 bit intervals for code-books A and B, respectively), and subtracting this product from R before the logarithm is taken. These results are shown in Fig. 9.

It had been hoped that such corrections would reduce the spread of the measured data for each coding method, but this was not so. However, it is reasonable to combine the results depicted in Figs. 7, 8 and 9, to give an overall picture of the performance of delay modulation, code-book A and code-book B. As shown in Fig. 10 this was done by taking an approximate mean of the 'pessimistic' lines of Figs. 7, 8 and 9.

Notice that all these curves tend to the general form of Fig. 11. The flatter part of the curve before the knee is reached is probably due in the main to a background of dropouts. Errors introduced by coding limitations begin to dominate at packing densities beyond the knee, so that a reasonable and practical choice of optimum operating point is the knee, or 'critical packing density' of user data, which coincides approximately with the 1 in 10^5 criterion as implied in Section 2.1.

If this criterion is applied to the results in Fig. 10, the critical packing density of user data for the three coding methods examined experimentally is:

Delay Modulation	26 k bit/inch (1·0 k bit/mm)
Code-book A	31 k bit/inch (1·2 k bit/mm)
Code-book B	32 k bit/inch (1·3 k bit/mm)

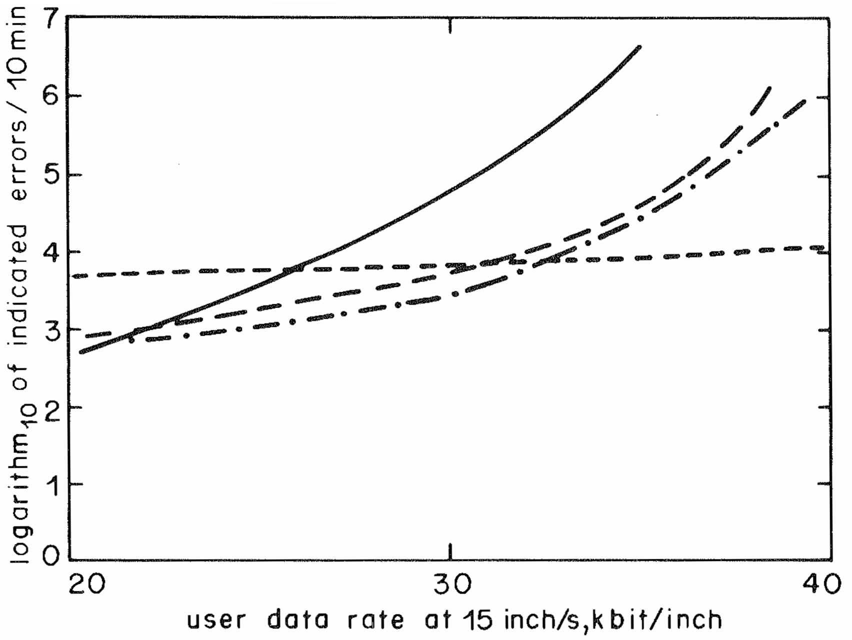


Fig. 10 - Overall performance

Delay modulation
Code-book A
Code-book B
Locus of 1 in 10^5 error rate (normalised)

It should be remembered that these values are for user data, the flux-transition density actually on the tape is higher by a factor n/k for code-books A and B, but it remains at the same value for delay modulation.

5.3. Performance with noise

The ruggedness of a coding system may usefully be assessed by measuring the amount of additional noise that can be injected into the communication link before the maximum permissible error rate is reached.

The noise in the experimental system was deliberately increased by injecting white noise into the replay head amplifier. The absolute level of the noise contributed by the head and tape, the amplifier, and typical equalisation was measured using an r.m.s. meter (thermocouple) and related to the injected noise level via a calibration curve.

Error rates R were obtained for a number of noise levels for each coding system at a small number of user-data rates, and were plotted in Fig. 12 against the absolute noise level measured after equalisation.

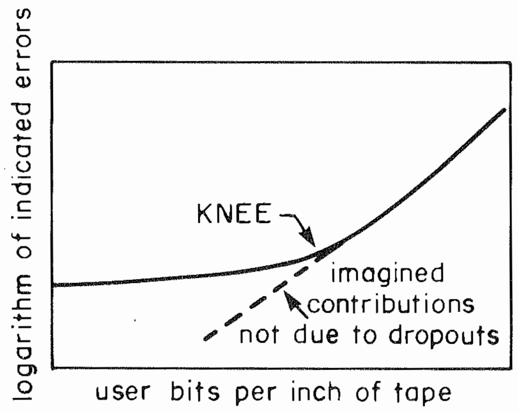


Fig. 11 - General form of results

Each graph is again of the form of Fig. 11 showing a critical noise level at which the errors begin to dominate the recording noise. The corresponding signal to noise ratios were obtained by measuring signal levels, again with an r.m.s. meter, and dividing them by the corresponding noise levels.

The critical signal to noise ratio for each of the three coding methods is plotted against the packing density of user-data in Fig. 13. Because of measurement difficulties, the shape and calibration of the curves in Fig. 13 are somewhat uncertain. However, the curves indicate that code-book B was, as expected in view of its higher low-frequency content, more susceptible to noise than code-book A, and that both code-books were less susceptible than delay modulation.

6. Conclusions

Tests have been made on the effectiveness of two block codes compared with delay modulation (Miller code) for improving the packing density of binary data recorded on magnetic tape. In the first block code (code-book A) blocks of seven coded bits represented five input data ('user') bits, and in the second code (code-book B) each block represented six user bits.

Compared with delay modulation, both of the block coded offered an increase in the packing density of user-data of about 20%, for a given error rate. Code-book B (7, 6) was selected in an attempt to improve on the performance of code-book A (7, 5) by increasing the efficiency at the expense of an increased range of string length, but no significant improvement was found. It is reasonable to conclude that no other seven-digit block-code could be chosen to improve the performance significantly. Longer codes could give an improved performance, but they might lead to impractical and costly equipment, mainly due to an exponential rise in the storage requirement which is roughly

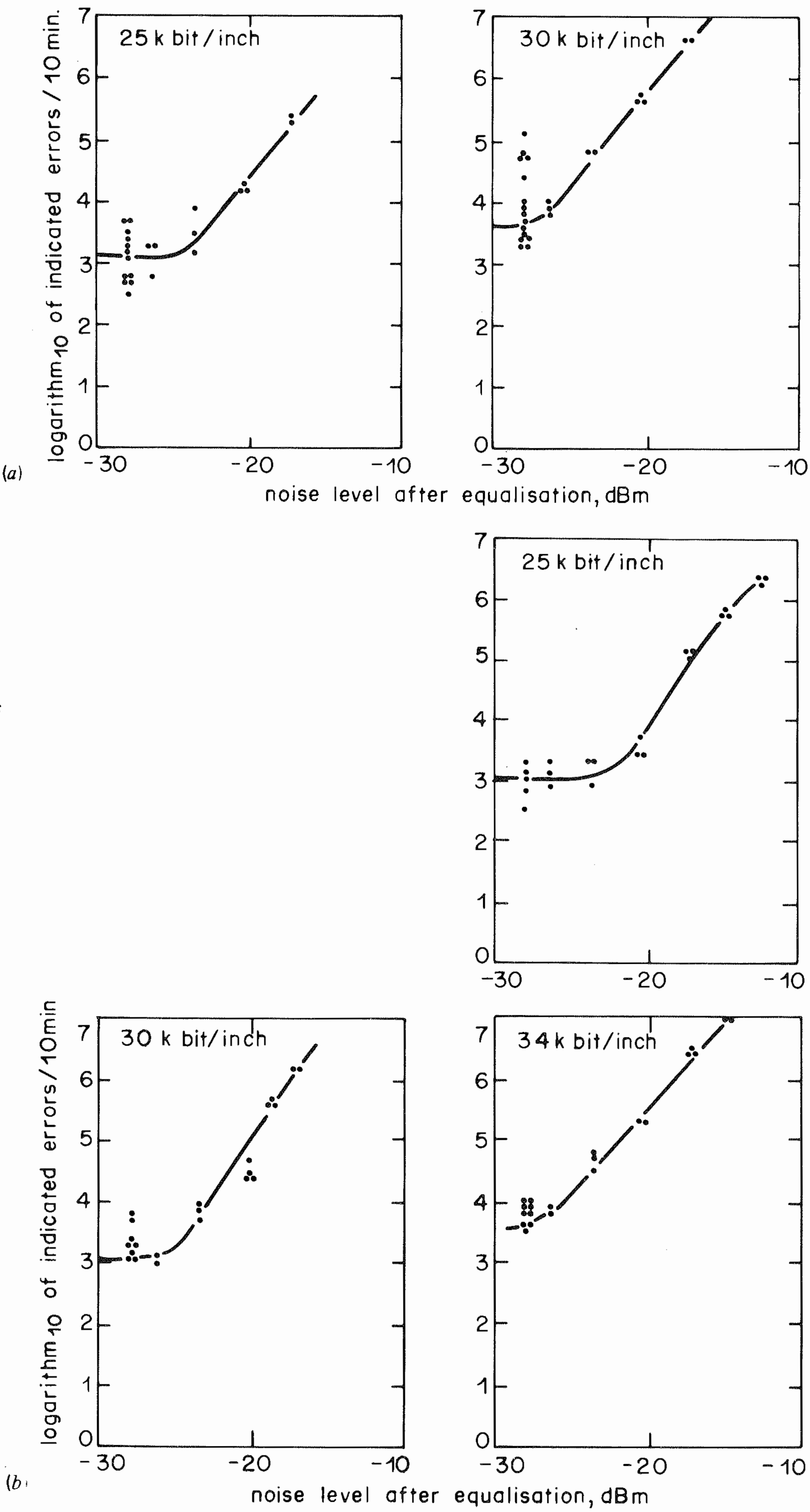
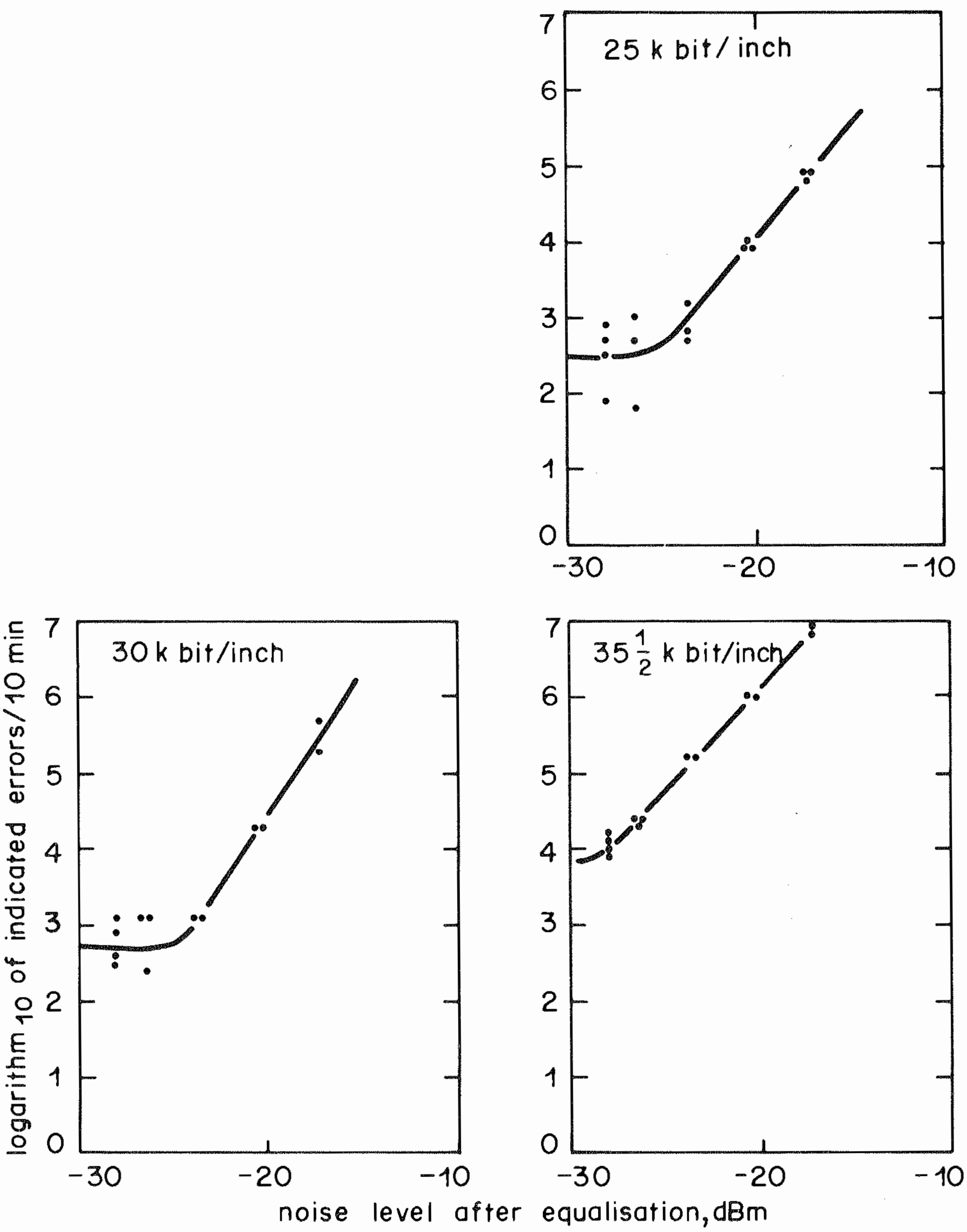


Fig. 12 - Error rate R versus channel noise level
(*a*) Delay modulation
(*b*) Code-book A



(c)

Fig. 12 - Error rate R versus channel noise level
(c) Code-book B

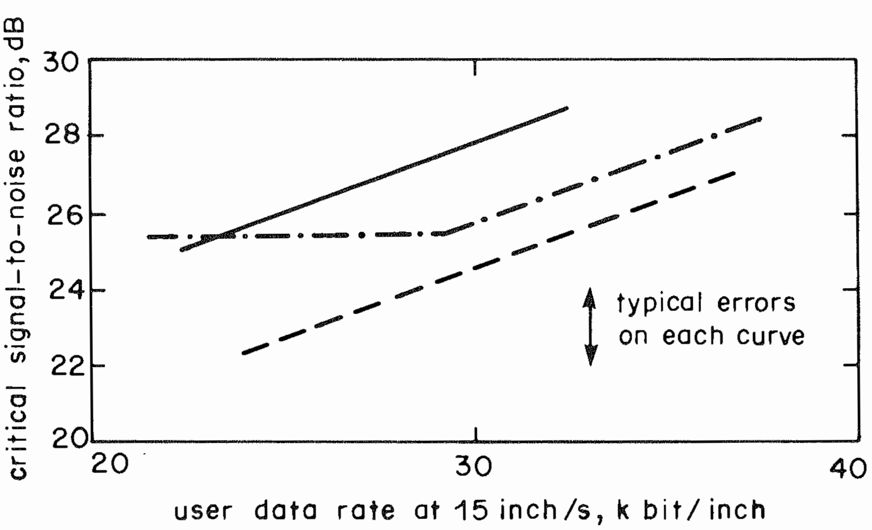


Fig. 13 - Overall noise performance
Delay modulation
Code-book A
Code-book B

proportional to $2^k + 2^n$. Indeed, even the cost of instrumenting code-books A or B is relatively high compared with delay modulation, especially for multi-channel recording applications.

A promising alternative modulation method was examined briefly; essentially, the method records a block code into NRZ 1, giving a likely increase in packing density of about 12% over that for code-book A. No experimental work was done with this 'coded NRZ 1' method; it is recommended that consideration be given to doing this.

7. References

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Appendix

Specification of the Experimental System

8.1. General

Tape:	3M Type 951 instrumentation tape; width 12·7 mm (½ inch)
Tape Speed:	38 cm/s (15 inch/s)
Record head gap:	1·5 μm (60 μinch)
Replay head gap:	0·8 μm (30 μinch)
Track Width:	0·64 mm (0·025 inch)
Signal to noise ratio:	30 dB r.m.s. approximately (see Section 5.3)
Equalisation:	See Section 8.2 below
Pseudo-random sequence length:	2^{10} bits, though tests were performed which showed negligible degradation in performance when using 2^{20} or 2^{60} bits.

8.2. Description of replay equalisers

The amplification and equalisation system used is shown in Fig. 14. The principle elements are L_b and C_b, which perform differentiation and band-limiting, respectively. R_b is adjusted to give a low Q of about 3. Additional high-frequency equalisation can be performed by tuning the tape-head inductance L_a frequency with C_a, the Q of this circuit being about 6. High-frequency dispersion is increased with this network, and becomes unacceptable for delay modulation at data rates much less than those for block codes. This is because timing information becomes progressively degraded as the recorded data rate is increased, and delay modulation has a clock rate of twice the user-data rate; for a block code the clock rate is the same as the recorded data rate, i.e. (n/k) times the user-data rate.

Two basic equalisations (a), which involves head resonance, and (b), where C_a is omitted, were instrumented and the element values are listed below. Slight variations for code-book B are in parenthesis. I_R is the peak to peak value of the record-current which was used, which can be thought of as an equalisation parameter as it affected amplitude frequency characteristics of the recording channel.

(a)		(b)	
C_a	= 750 pF	C_a	omitted
R_b	= 3·5 kΩ	R_b	= 4·7 kΩ
C_b	= 150 pF (200 pF)	C_b	= 220 pF
I_R	= 16 mA (19 mA)	I_R	= 18 mA (21 mA)

For each measurement, these values were optimised for maximum eye-height and eye-width of the equalised signal. The resulting peak-signal frequency characteristics for a square-wave input are compared with that with no equalisation in Fig. 15. Amplitude and phase characteristics for the equalisers, measured with a sinusoidal signal, are shown in Fig. 16, showing greater dispersion for (a) than for (b).

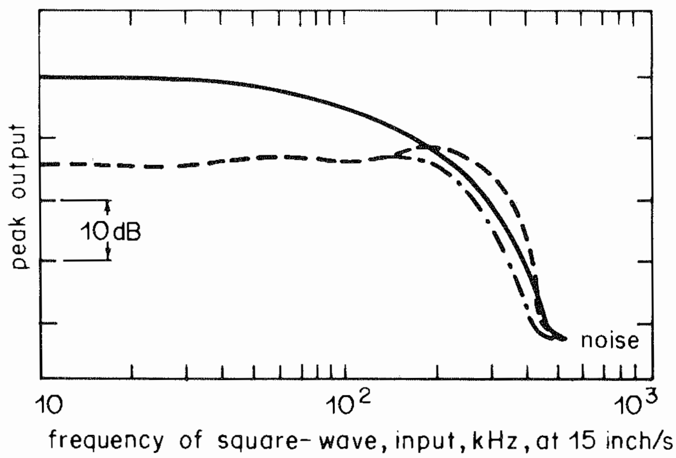

Fig. 15 - Peak-signal characteristic with equalisation

————	No equalisation
— — — —	With equalisation (a)
—— · —— ·	With equalisation (b)

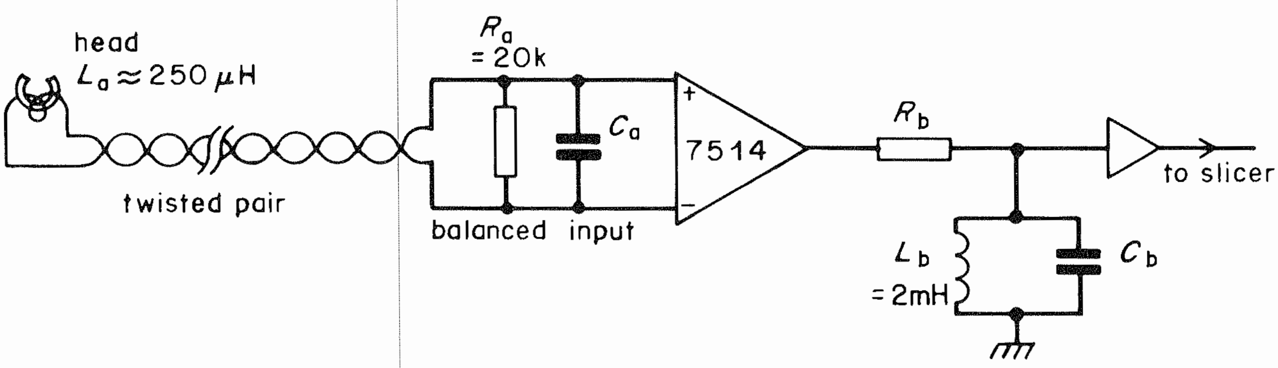

Fig. 14 - Replay amplifier and equalisation

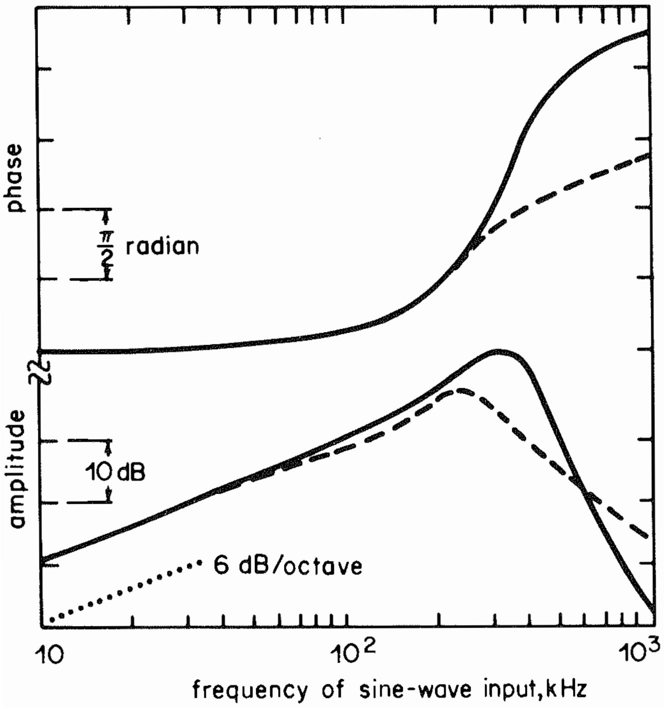

Fig. 16 - Phase and amplitude characteristics of equalisation

Equalisation (a) Equalisation (b)

For delay modulation equalisation (b) was found to be suitable at all data rates investigated. Equalisation (a) gave no improvement because of the loss of the requisite high-rate timing information.

For both of the block codes, equalisation (a) gave the better performance at all the data rates investigated.

8.3. Description of coders and decoders

Both the coder and decoder clock signals were provided by voltage controlled oscillators (VCOs), whose output was divided appropriately to give user and coded data-rate clocks. Such clocks were directed to a delay modulation coder and decoder[2] or to the block coders and decoders.

In terms of hardware, each block coder differed from its decoder only in the required amount of storage. In both, the incoming serial bit stream was converted to parallel words of the appropriate block length, coded or decoded using PROM* storage, and reserialised at the new rate.

* Programmable Read Only Memory.

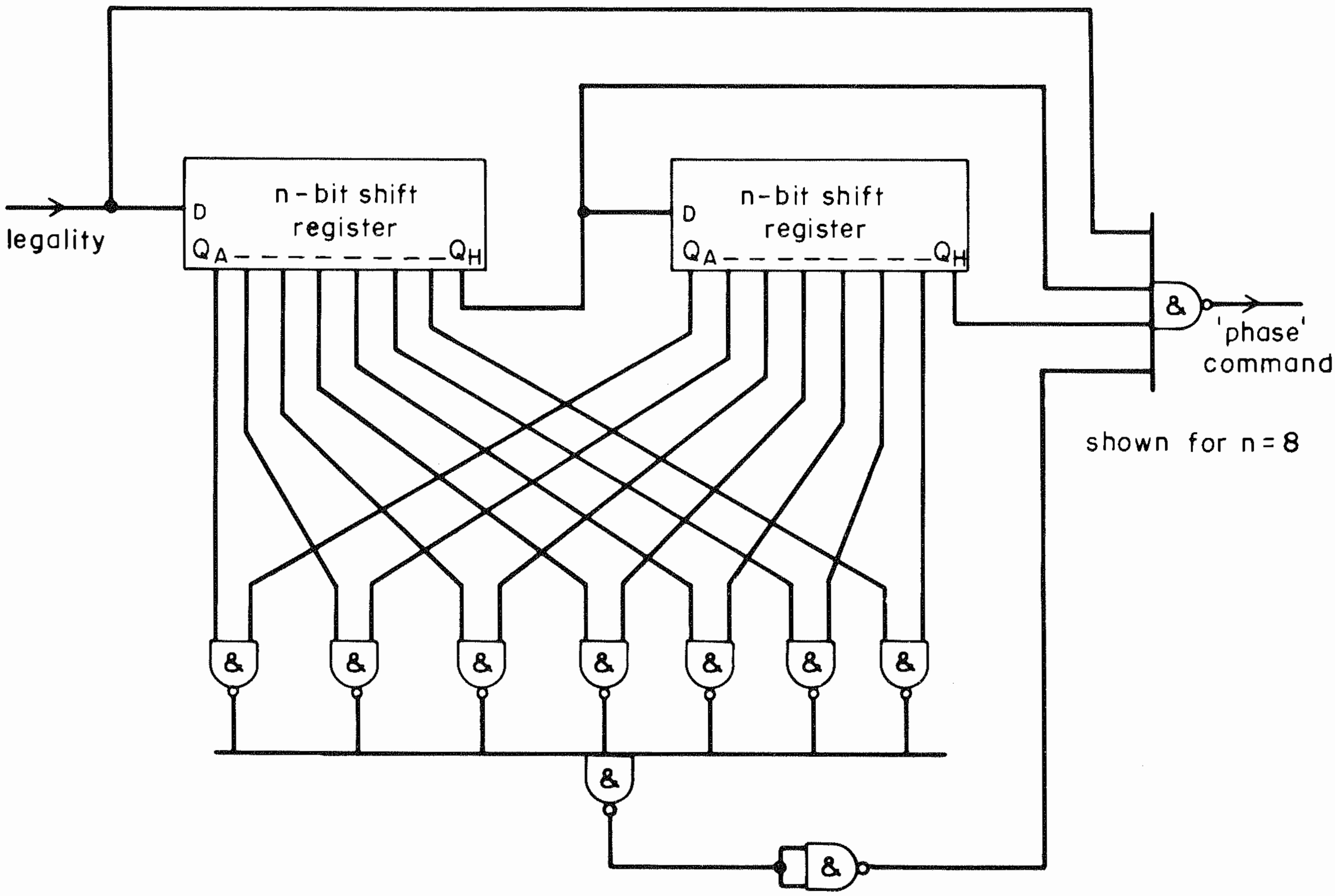

Fig. 17 - Logic for the rephasing algorithm

8.4. Clock regeneration

The coder VCO was set for the desired user or coded data-rate. To regenerate clock signals, the corresponding decoder VCO was phase locked to a pulse waveform generated from the replayed coded data; the waveform comprised a pulse for each flux-reversal on the tape, which was then suitably shaped. In addition, the phase of the regenerated clock signal was adjusted for each measurement to give the optimum result.

The phase-lock loop was arranged to remain in lock for string lengths far exceeding those of the modulation codes used, but nevertheless able to follow short-term phase fluctuations to some extent.

8.5. Self phasing for block codes

The block decoders differed from the block coders in that provision was made both to detect illegal code-words, and to change the phase at which block coding or decoding occurred.

The algorithm used to determine the correct phase was as follows:

For each coded-data bit entered into a code-book decoder, an attempt is made to decode the previous n digits. If and only if this digit group is a member of the code-book is the legality flag set to one. Legality is aggregated in each of the possible n phases until three consecutive flags occur for a particular phase. Use is now made of the existence of at least some illegal groups in each of the other phases. If three consecutive flags occur in a particular phase, and in each of the other phases there are not two consecutive flags, a 'phase' command is issued to the clock generator and coded-data is subsequently interpreted in that phase. This algorithm was found to give a sufficient, practical indication of the correct phase. The logic required to generate the phase command is shown in Fig. 17.

The frequency of occurrence of phase commands depends on the code-book. Phasing information was found experimentally to be contained, on the average, within every 66 and 155 consecutive bit cells of user-data, for code-books A and B respectively. For signals with a 50% error rate, the average interval between phase commands, which are then meaningless, increases by a factor of about five. This gives a measure of protection against false phase commands during error bursts.

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